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PERIODIC STATES IN A PRESSURIZED FLOW SHOWING A PHASE TRANSITION

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The scope for long-term operation in periodic mode is examined for a pipeline carrying a liquid that can freeze.

A phase transition may occur in a pressurized liquid in a pipe, an example being provided by a pipeline carrying a liquid when the environmental temperature is below the freezing point [1, 2]. There are several papers [3-5] on the effects of phase transitions on flow-pressure characteristics. The studies concern states where a layer of frozen liquid is formed on the inner surface, which increases the hydraulic resistance and thus raises the pumping energy required. Therefore, when a pipeline is designed for such conditions, the insulation parameters are usually chosen to prevent a frozen layer from forming. However, the insulation may be damaged on some parts of the line, and if those are sufficiently extended, this is immediately reflected in the thermal and hydraulic conditions, and one can detect the insulation damage from the changes in flow-pressure and temperature characteristics. The operations are only slightly affected by short damaged parts, but the growth of a frozen layer there may block the pipe. One therefore has to examine the long-time operation for a pipe having damaged insulation.

A pipeline may be operated with pumping halts, which greatly increase the blocking hazard. It is therefore of interest to estimate the permissible halt time and to examine the scope for periodic operation.

Here we consider flow in a circular pipe for a viscous liquid at temperature T_1, where the freezing temperature T_* is above the environmental temperature T_0. Under those conditions, the liquid may freeze and form an internal surface r_*. We consider a short pipe $(2\pi k_2 R/\rho_2 c_2 Q\ell \gg 1)$, through which the liquid is pumped with flow rate Q.

We assume that the characteristic thermal and hydrodynamic relaxation times are much less than the characteristic phase-transition time, so

$$\rho_1 c_1 \frac{\partial T}{\partial t} = \frac{\lambda}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right), \quad r_* < r < R, \tag{1}$$

$$\lambda \frac{\partial T}{\partial r} + k_1 (T - T_0)|_{r=R} = 0, \tag{2}$$

$$T|_{r=r_*} = T_*, \tag{3}$$

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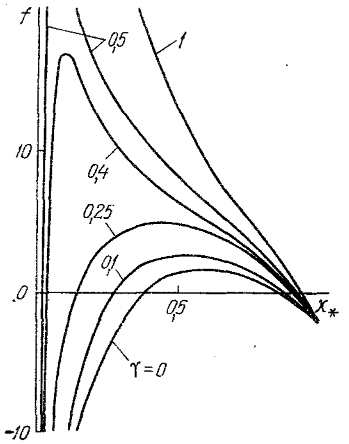


Fig. 1

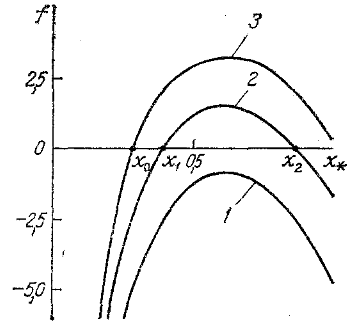


Fig. 2

Fig. 1. $f(x_*)$ for various γ.

Fig. 2. Behavior of $f(x_*)$: 1) $a = 18$, $\alpha_1 = 2$, $b = 23$; 2) $a = 18$, $\alpha_1 = 2$, $b = 20.2$; 3) $a = 18$, $\alpha_1 = 2$, $b = 18$.

$$T = T_1,\ 0 \leqslant r \leqslant r_*, \tag{4}$$

$$\rho_2 (c_2 (T_1 - T_*) + q) \frac{dr_*}{dt} = k_2 (T_1 - T_*) + \lambda \left.\frac{\partial T}{\partial r}\right|_{r=r_*+0}. \tag{5}$$

We introduce the dimensionless variables $\Theta = (T - T_0)/(T_1 - T_0)$, $\Theta_* = (T_* - T_0)/(T_1 - T_0)$, $x = r/R$, $x_* = r_*/R$, $\tau = \kappa t/R^2$, $\beta = q/c_2(T_1 - T_*)$, $\alpha_i = k_i R/\lambda$, $i = 1, 2$ and use the quasistationary approximation for the temperature in the frozen zone to get

$$\frac{dx_*}{dt} = \frac{\alpha_2 (1 - \Theta_*)}{1 - \Theta_* + \beta} - \frac{\alpha_1 \Theta_* x_*^{-1} (1 - \alpha_1 \ln x_*)^{-1}}{1 - \Theta_* + \beta}, \tag{6}$$

which describes the change in frozen-zone size during the pumping period.

The coefficient α_2 is given by standard empirical formulas [1, 6]: the dependence of α_2 on the cross section radius x_* is $\alpha_2 = Ax_*^{\gamma}$, $0 \leq \gamma \leq 1$, $A > 0$. Graphs have been drawn for the right side of (6),

$$f(x_*) = ax_*^{-\gamma} - bx_*^{-1} (1 - \alpha_1 \ln x_*), \tag{7}$$

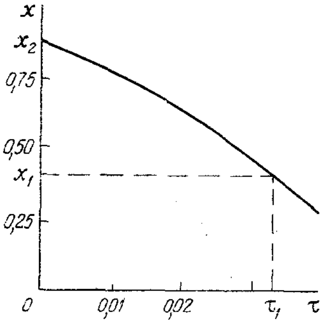
where

$$a = \frac{A(1 - \Theta_*)}{1 - \Theta_* + \beta},\quad b = \frac{\Theta_* \alpha_1}{1 - \Theta_* + \beta},$$

for various γ in Fig. 1 ($a = 18$; $\alpha_1 = 2$; $b = 20.2$). $\gamma = 0.03$ in laminar flow. We therefore put $\gamma = 0$ in (7) to get a good lower bound to the radius change. Then $f(x_*)$ may take one of the following forms for various a, b, and α_1. For $p_1 = ba^{-1} > 1$ and $p_2 = ba^{-1}\alpha_1 \exp(1 - \alpha_1{}^{-1}) > 1$, there are no stationary states (curve 1 in Fig. 2) and the pipeline cannot be operated on a long-time basis, since the frozen layer accumulates monotonically and blocks the pipe. For $p_1 > 1$ and $p_2 < 1$ or with $p_1 \leq 1$ (curves 2 and 3 in Fig. 2 correspondingly), there is a stable stationary state (no frozen layer for curve 3, or $x_* = x_2$ for curve 2) together with an unstable state (correspondingly $x_* = x_0$ and $x_* = x_1$). Curve 3 is characteristic of insulation design parameters. If the insulation is damaged, the case corresponding to curve 1 leads to an inevitable accident. In the cases of curves 2 and 3, the time for which the pipeline may be shut down is determined by the time τ_1 for the frozen layer to attain a size corresponding to the unstable stationary state.

We consider what occurs after the pumping is halted. Here (1)-(3) apply and

$$\rho_2 (c_2 (T - T_*) + q) \frac{dr_*}{dt} = k_3 (T - T_*) + \lambda \left.\frac{\partial T}{\partial r}\right|_{r=r_*+0}, \tag{8}$$



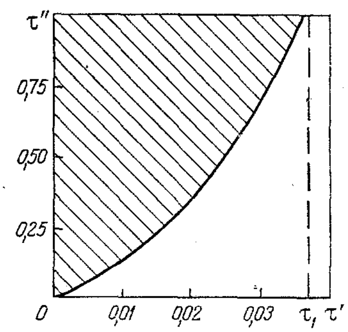


Fig. 3 Fig. 4

Fig. 3. Dimensionless transmission cross section radius as a function of time during pumping halt.

Fig. 4. Parameter region corresponding to long-time pipeline operation in periodic mode.

$$c_2\rho_2 \frac{dT}{dt} = \frac{2k_3}{r_*}(T_* - T), \; 0 \leqslant r \leqslant r_*, \tag{9}$$

where k_3 is the heat-transfer coefficient from the unfrozen liquid to the frozen layer in the shut-down pipe, which is defined by an empirical formula [1], which takes the form $\alpha_3 = k_3R/\lambda = Bx_*^{-\gamma}$, $B > 0$, $\gamma = 0.14$.

As there is a quasistationary temperature distribution in the frozen layer, (8) and (9) are written in dimensionless variables as

$$\frac{dx_*}{d\tau} = Bx_*^{-\gamma} - \frac{\alpha_1\Theta_*}{\Theta - \Theta_* + \beta} x_*^{-1}(1 - \alpha_1 \ln x_*)^{-1}, \tag{10}$$

$$\frac{d\Theta}{d\tau} = \frac{2B}{x_*^{1+\gamma}}(\Theta_* - \Theta), \; 0 \leqslant x \leqslant x_*. \tag{11}$$

Figure 3 shows the size of the frozen zone when the pumping is halted ($\alpha_1 = 2$; $B = 3.42$; $\Theta_* = 0.95$; $\beta = 0.05$). The instant when x_1 is attained represents the permissible halt time.

It is necessary to solve (6) with (10) and (11) in order to elucidate long-time periodic operation.

One of the following forms applies for the τ dependence of x_* for various relations between the shut-down time τ' and working time τ'': monotonic frozen-layer accumulation, blocking after several periods, and long-time periodic operation.

The relation between τ' and τ'' governs the scope for long-time periodic operation. For a given $\tau' < \tau_1$, the restart time τ'' should be greater than a certain τ_2. The τ' dependence of τ_2 ($a = 18$; $b = 20.2$; $\alpha_1 = 2$; $B = 3.42$; $\Theta_* = 0.95$; $\beta = 0.05$) is shown in Fig. 4. The hatched region corresponds to long-time periodic operation. The calculations correspond to the following pumping parameters: $R = 0.2$ m, $\nu = 10^{-5}$ m²/sec, $\rho = 10^3$ kg/m³, $c = 2 \cdot 10^3$ J/(kg·K), $w = 0.25$ m/sec, $\lambda = 0.15$ W/(m·K), $\xi = 10^{-3}$ 1/K, $T_1 - T_* = 3$ K, $q = 300$ J/kg, $k_1 = 1.5$ W/(m²·K). Parameters A and B are given by [1]

$$A = 0.085\,\mathrm{Re}^{0,33}\mathrm{Pr}^{0,43}\mathrm{Gr}^{0,1} = 36.4; \; B = 0.165\,(\mathrm{GrPr})^{0,14} = 3.42.$$

The permissible shut-down time is 5.3 h. Figure 4 enables one to evaluate the scope for long-time periodic operation.

These studies enable one to estimate the working time for a particular pipeline with a short length of damaged insulation. In particular, if the insulation is completely destroyed over a section (maximum k_1) and τ' and τ'' do not correspond to the hatched region (Fig. 4), one can get an emergency due to blocking. Such insulation damage over a short section can be detected from the hydraulic characteristics if there is a considerable reduction in the clear cross section (in the zone $x_* < x_1$), i.e., when the freezing has become irreversible. In such a situation, a particularly careful check is needed on the insulation along the pipe.

NOTATION

t, time; T, temperature; r, radial coordinate; ℓ and R, pipe length and radius, ρ_1 and ρ_2, densities of frozen layer and liquid; c_1 and c_2, specific heats of frozen layer and liquid; λ, thermal conductivity of liquid; q, latent heat of phase transition; r_*, clear cross section radius; k_1, heat-transfer coefficient for frozen layer to environment; k_2, heat-transfer coefficient from flow to frozen zone; $\kappa = \lambda/\rho_1 c_1$, thermal diffusivity for frozen layer; $Re = 2wR/\nu$, Reynolds number; $Gr = 8R^3\xi g(T_1 - T_*)/\nu^3$, Grashof number; $Pr = \nu\rho_2 c_2/\lambda$, Prandtl number; ν, kinematic viscosity; w, flow speed; g, acceleration due to gravity; ξ, bulk expansion coefficient.

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EFFECTS OF WATER SPEED AND TEMPERATURE ON ICING IN THERMAL SIPHONS

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A numerical study has been made on the freezing in a thermal siphon immersed in water with free or forced convection. The effects of various factors on the ice column diameter are examined.

In the construction of major pipelines in West Siberia, an important part is played by traverses through rivers, lakes, and lowland areas generally. There are persistent negative air temperatures, which are maintained for long periods in such places, which can give rise to ice or frozen-soil environments. However, the carrying capacity of such ice is usually insufficient to allow access to heavy vehicles or constructional machinery. To strengthen the load capacity of such crossings, one installs wooden structures and freezes the ice by means of thermal siphons.

A construction proposed in [1] for an ice crossing with frozen cylindrical columns can reduce the time and cost of construction and increase the load capacity, particularly if the underlying ground is soft.

One begins to install such ice bridges after a continuous ice sheet 10-15 cm thick has formed naturally. The evaporative parts of the siphons are inserted through holes drilled in the ice cover, which extend into the underlying soil. When the ice columns are formed, the soil is also frozen around the buried part of the siphon. The frozen soil provides a reliable base for the ice column and does not yield. Such ice columns in ice crossings can be used on winter vehicle roads and can increase the load capacity of the ice cover by a factor 1.5-2.

The freezing around a siphon is determined mainly by the surrounding air temperature, the water temperature, and the wind and water speeds. The availability of a structure for

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